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Flow Control for Supersonic Inlet Applications

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14. ABSTRACT

This reports provides a summary of research conducted over a period of 2 ½ years into the application of micro---vortex flow control to supersonic mixed compression inlets. The research performed under this contract has led directly or contributed to a significant number of conference and journal publications. The ley lessons learned are described and illustrated with relevant data. Archival publications are given for further reading as they provide more detailed information. The purpose of this report is to summarize the body of work and highlight the most significant findings in the context of supersonic inlet flows. As a result of this research, 'lessons learned' are given in Section 7 of the final technical report which are relevant to future inlet design and development.

15. SUBJECT TERMS

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Flow Control for Supersonic Inlet Applications

Final Report on Grant No. FA8655-11-1-3002

Holger Babinsky

March 2014

Research Outputs:

This reports provides a summary of research conducted over a period of 2 ½ years into the application of micro-vortex flow control to supersonic mixed compression inlets. The research performed under this contract has led directly or contributed to a significant number of conference and journal publications[1]:

1. Burton, D.M.F. & Babinsky, H., "Corner Separation Effects for Normal Shock Wave/Turbulent Boundary Layer Interactions in Rectangular Channels", *Journal of Fluid Mechanics*, Volume 707, pp. 287-306, September 2012
2. Titchener, N., Babinsky, H., "Shock wave/boundary-layer interaction control using a combination of vortex generators and bleed", *AIAA J.*, Vol.51, No.5, pp. 1221-1233, May 2013
3. Loth, E., Titchener, N., Babinsky, H., Povinelli, L., "Canonical NSBLI Flows Relevant to External Compression Inlets", *AIAA J.*, Vol.51, No.9, pp. 2208-2217, September 2013
4. Titchener, N., Babinsky, H., "Control of a Shock-Wave/Boundary-Layer Interaction and Subsequent Subsonic Diffuser Using a Combination of Vortex Generators and Bleed", AIAA-2012-274, 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Nashville, Tennessee, Jan. 9-12, 2012
5. Oorebeek, J.M., Babinsky, H., "Comparison of Bleed and Micro-Vortex Generator Effects on Supersonic Boundary-Layers", AIAA-2012-45, 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Nashville, Tennessee, Jan. 9-12, 2012
6. Titchener, N., Babinsky, H., "Can Fundamental Shock-Wave/Boundary-Layer Interaction Research be Relevant to Inlet Aerodynamics?", AIAA-2012-17, 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Nashville, Tennessee, Jan. 9-12, 2012
7. Loth, E.L., Titchener, N., Babinsky, H., Povinelli, L.A., "A Canonical Normal SBLI Flow Relevant to External Compression Inlets", AIAA-2013-0016, *51st Aerospace Sciences Meeting*, Grapevine, Texas, 2013 (Invited)
8. Titchener, N., Babinsky, H., Loth, E.L., "The Effects of Various Vortex Generator Configurations on a Normal Shock Wave / Boundary Layer Interaction", AIAA-2013-0018, *51st Aerospace Sciences Meeting*, Grapevine, Texas, 2013 (Invited)
9. Babinsky, H., Oorebeek, J., Cottingham, T.G., "Corner effects in reflecting oblique shock-wave/boundary- layer interactions", AIAA-2013-0859, *51st Aerospace Sciences Meeting*, Grapevine, Texas, 2013 (Invited)

The research also contontributed to the training of two graduate students, Neil Titchener and Joseph Oorebeek:

1. Titchener, N., "An experimental investigation of flow control for supersonic inlets", PhD thesis, University of Cambridge, 2013
2. Oorebeek, J.M., PhD thesis, University of Cambridge, to be submitted 2014

Al relevant articles and copies of the thesis have been/will be provided to AFRL.

[1] Further articles are currently in preparation.

Summary of Research Findings

In the following, the ley lessons learned are described and illustrated with relevant data. Archival publications are given for further reading as they provide more detailed information. The purpose of this report is to summarise the body of work and highlight the most significant findings in the context of supersonic inlet flows.

1. Introduction:

High speed flows inside supersonic mixed or external compression inlets feature many important aerodynamic challenges. The research conducted under this contract advanced our current understanding in several key areas relevant to inlets: Shock-wave boundary-layer interactions (SBLIs), normal shock/diffuser flowfields, sidewall/corner effects and micro-vortex generator separation control. All of the work reported here has been performed in the Engineering Department's supersonic blow-down wind tunnels. Detailed descriptions of operating conditions and geometries are provided in the various research articles listed at the end of the report (and referenced accordingly throughout). It is worth emphasising however, that the facility is capable of generating relatively high Reynolds numbers (for a small research facility) in a range close to those experienced in full scale inlets. For example, the Reynolds number based on floor/sidewall boundary-layer displacement thickness is typically of the order of 15-20,000, while the Reynolds number based on tunnel width/height (i.e. the equivalent of an inlet dimension) is in the range of 5-8 million.

In the following, the research findings are grouped by thematic headings. In this report, only the 'headline' results and findings are reported while the supporting data and more detailed arguments can be found in the accompanying scientific papers.

2. Corner flow effects:

Many inlets of practical interest feature geometries with internal corners formed by the intersections of side and floor surfaces. Most fundamental research in SBLIs is performed in wind tunnels with rectangular cross-sections. Therefore, the flow inside streamwise corners is of considerable practical interest – unfortunately most previous research has concentrated on regions far away from sidewalls and ignored effects caused by the presence of corner flows. At Cambridge University we have studied this issue for some time (partly supported by previous AFRL grants) and because of the direct relevance to the current research the main findings are briefly summarised here. The main point of interest is the influence of sidewalls (and the streamwise corner formed by the sidewall/floor junction) on oblique and normal SBLIs as shown schematically in fig. 1.

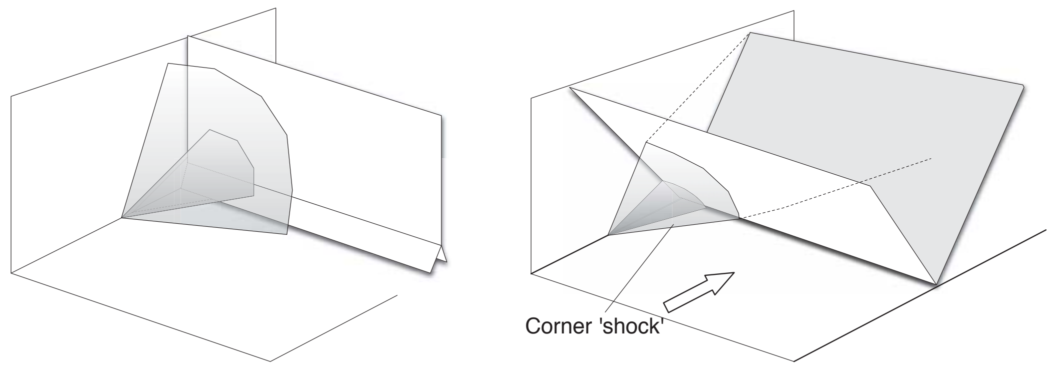


Figure 1: Corner flow influence in normal SBLI (Left) and oblique impinging SBLI (right)

For incident shocks strong enough to cause flow separation, the footprint of the separation regions on the floor is similar for both scenarios: Typically, there is a central separation and a corner separation [8, 11]. Often these two separation regimes are unconnected and a 'channel' of attached flow can be seen in between (as shown in fig. 2). In weak cases the central separation may be absent. For stronger shock waves – more severe adverse pressure gradients – a 'merged' separation region encompassing both the corner and the central separation is common. It is important to note that the onset of corner separation always occurs ahead of any central separation.

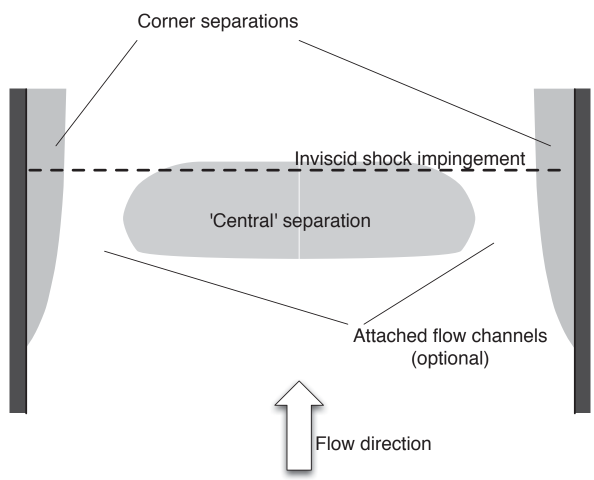
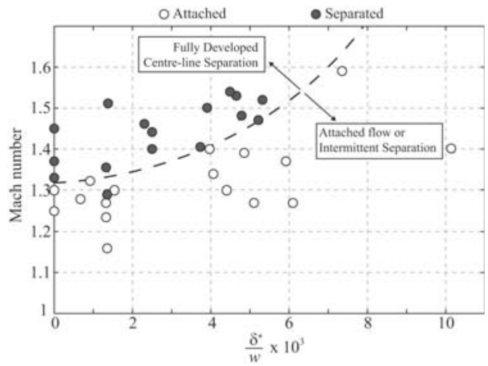


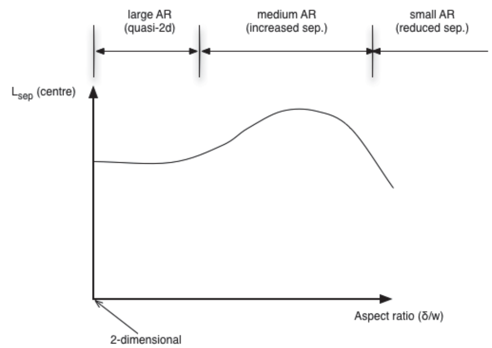
Figure 2: Typical separation pattern observed below an SBLI, consisting of a main (central) separation and two corner separations on either side. Here, these two types of separation are separated by a 'channel' of attached flow – for more extensive separation it is common to observe all separation zones to merge

Our research (as well as a parallel study performed at AFRL [12]) has shown that the onset, size and shape of shock-induced separation around the centreline of a channel floor is strongly influenced by the presence of side-walls. The main effects are well captured by the 'viscous aspect ratio' (the ratio of boundary-layer thickness to channel width), as shown in fig. 3 [3, 8, 11].

In the normal SBLI case, these 3-D effects cause a delay of separation in the centre of the channel with increasing confinement as illustrated in fig. 3a. The situation is more complex in the oblique shock reflection case where confinement can both increase or decrease the size of separation (fig. 3b). This topic continues to be a subject of active research [12]).



a) separation onset in normal SBLIs



b) size of central separation in oblique shock reflections

Figure 3: Effect of 'viscous aspect ratio' on shock induced separation.

In both types of SBLI the main cause of three-dimensional effects is the presence corner separation which generates 'corner-shocks' (or compression waves) that alter the flowfield elsewhere.

A further outcome of this research is the understanding that different separation regions in a supersonic channel flow can influence each other. This is particularly noticeable in the transonic normal SBLI where it is often found that as one separation region increases in size another reduces and vice versa[2]. Flow control can therefore not be studied by its effects on a single separation zone in isolation.

The implications of these findings are that spanwise dimensions of transonic and supersonic channel flows are more important than at first thought and, more importantly, that the correct prediction of corner separation is an essential requirement in the correct simulation of such flowfields with CFD. More details can be found in the attached articles [3, 6, 8, 11, 12].

3. 'Inlet relevant' flowfield:

In order to study flows relevant to real-life supersonic inlets, while at the same time avoiding the complexity of realistic geometries, a canonical flowfield has been developed in Cambridge. This is deemed to represent a realistic flow 'challenge', whilst still being simple enough to allow for parametric investigations. The particular flow problem identified as being crucial for all types of supersonic inlet is the interaction of the final ('terminal') shock wave (generally a normal or near-normal shock) with the sidewall/floor boundary layer combined with the additional pressure gradient of a subsonic diffuser as sketched in fig. 4.

[2] Examples for this behavior are given in section 4, discussing the effects of flow control.

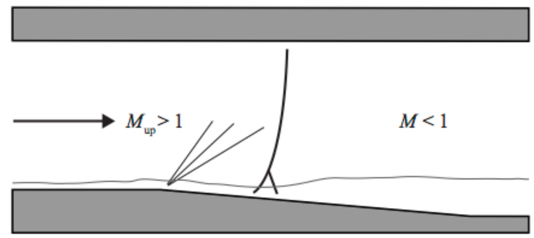


Figure 4: The normal-shock/diffuser flowfield: a critical element of supersonic inlet flows

Depending on the location of the shock wave relative to the diffuser entrance this scenario can either replicate a typical external inlet problem (where the shock wave sits some small separation distance ahead of the diffuser entrance) or a mixed compression inlet scenario (when the shock is located inside the diffuser as sketched in fig. 4). A detailed literature survey was performed which collected data on a wide variety of research inlet configurations [10]. This identified the flowfield shown in fig. 5 as an ideal set-up for fundamental studies of the SBLI-diffuser problem with a high relevance for current and future supersonic inlet scenarios. We refer to this flow configuration as the 'inlet-relevant' flowfield.

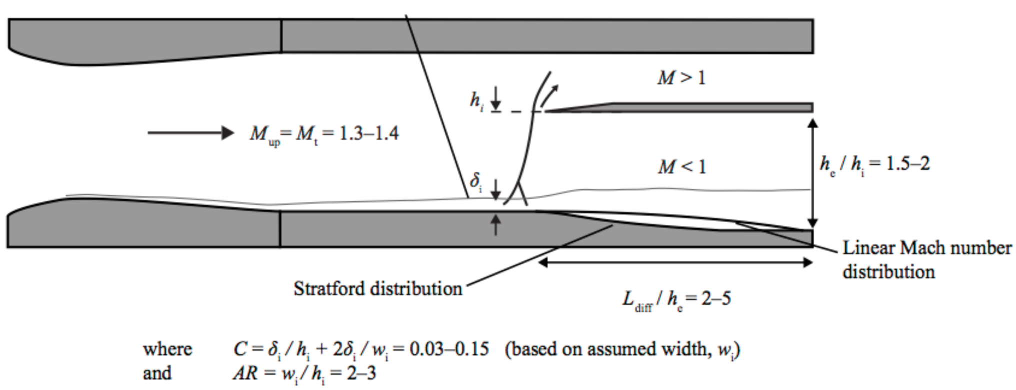


Figure 5: The 'inlet relevant' flowfield as a basis for fundamental studies [see 10]

In the flow shown in fig. 5, the terminal (near-normal) shock wave is artificially stabilised in position by a 'shock holding plate' (for more details, see [1]). This decouples the shock position from the diffuser flow – otherwise a large diffuser separation could cause severe flow oscillation and prevent detailed flow studies.

Investigations of this canonical flowfield [4,7,9] led to the following key findings:

- When the SBLI occurs upstream of the diffuser inlet as seen in fig. 6 (similar to an external compression scenario) even a short separation (or 'stand-off-') distance is sufficient to allow the boundary layer to recover before entering the diffuser. Thus, for moderate shock strengths ($M_S \leq 1.4$) and diffuser angles ($\alpha \leq 6°$) there is no significant separation in the diffuser. However, even in this 'benign' case there is a corner separation which originates at the SBLI and which grows as it enters the diffuser.

- As soon as the shock-induced adverse pressure gradient merges with the diffuser adverse pressure gradient[3] (once the shock moves inside the diffuser) the flowfield exhibits very significant flow separation – rendering the diffuser ineffective unless flow control is employed. This is illustrated by 7. The separation first originates in the corners (slightly ahead of the SBLI) and grows quickly to encompass the whole floor region either underneath the shock (for strong shocks) or some distance behind the shock (for weaker shocks). Clearly the combined diffuser and SBLI pressure gradients are a considerable problem for the flow, even for relatively benign diffuser angles of around 6°. This is a challenge for the design of mixed compression inlets.

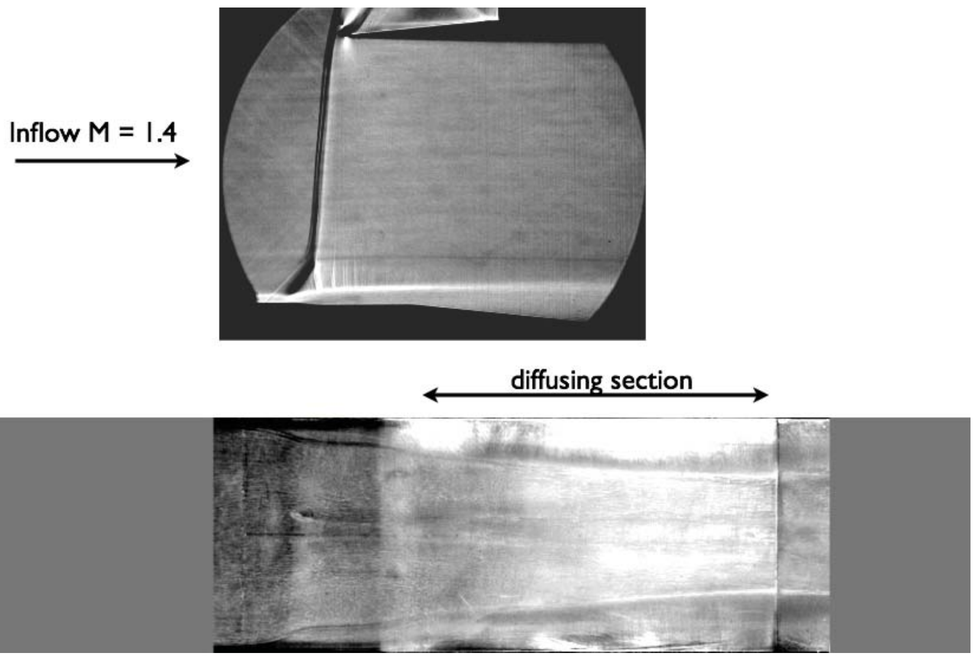


Figure 6: Schlieren image and surface oil-flow visualisation (on floor) for the 'inlet-relevant' flowfield with M=1.4 normal shock located upstream of 6° diffuser. Apart from separations in the corners formed by the floor-sidewall junction the main flow is attached along the floor of the diffuser section.

[3] For representative shock strengths and diffuser angles as set out in [10].

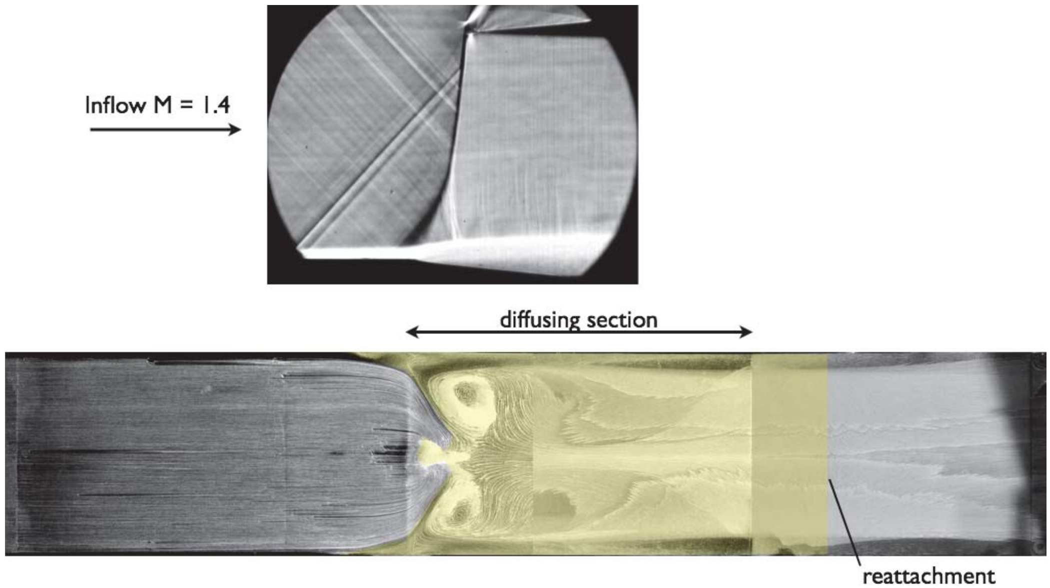


Figure 7: Schlieren image and surface oil-flow visualisation for the 'inlet-relevant' flowfield with the shock located inside the diffuser. There is significant separation along the wind tunnel floor (highlighted in yellow), rendering the diffuser ineffective (note the trajectory of the boundary layer edge in the schlieren photograph).

Experiments have also been performed on a similar configuration but without shock stabilisation as shown in fig. 8, hereafter referred to as 'un-stabilised normal shock/diffuser flowfield'. The aim of these investigations is to investigate the link between flowfield separation and shock motion. Due to the inherent unsteadiness of this flowfield it was not possible to obtained detailed flow measurements (e.g. LDV velocity data) and the results shown can only re-present time-averaged information.

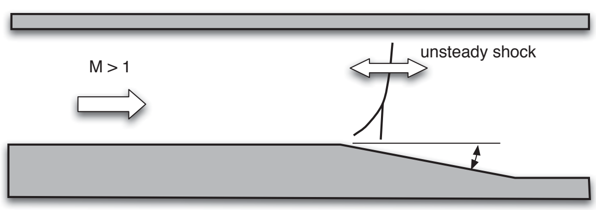


Figure 8: Un-stabilised normal shock/diffuser flowfield

These experiments confirmed the findings of the stabilised tests. Figure 9 shows the extent of flow separation on the diffuser floor and sidewall (from flow visualisation) which is very similar to that observed earlier in the stabilised experiments.

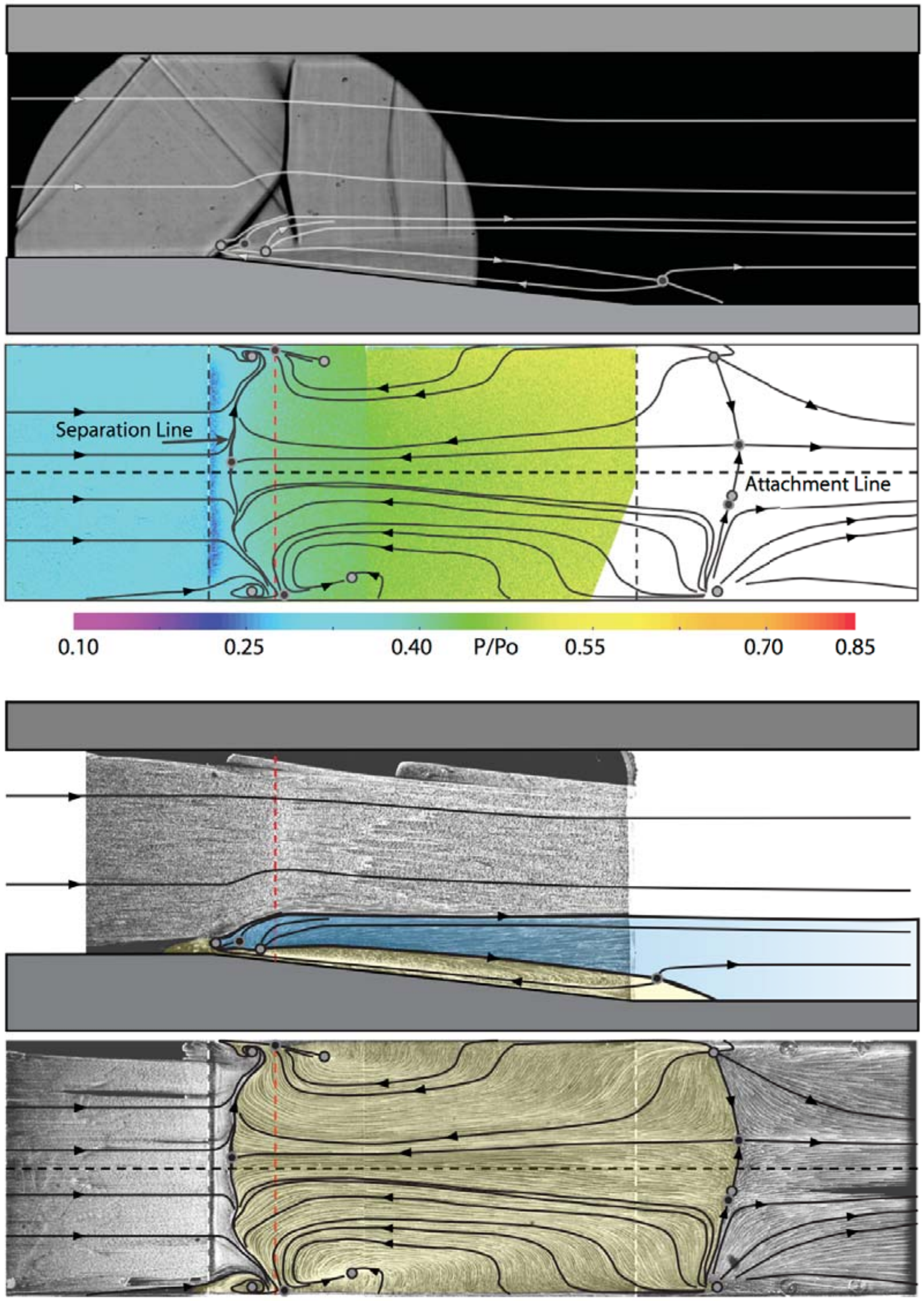


Figure 9: Compound image of schlieren (top), PSP (2nd from top), surface oil-flow (sidewall: 3rd from top, floor: bottom) and superimposed flow topology for the un-stabilised shock/diffuser flow-field (M=1.4, 6° diffuser angle). Estimated flow topology is superimposed where appropriate.

As expected, this flowfield exhibits considerable unsteadiness. Figure 10 shows a spectrum of shock oscillation as well as a histogram of shock position, obtained from analysis of high-speed schlieren video.

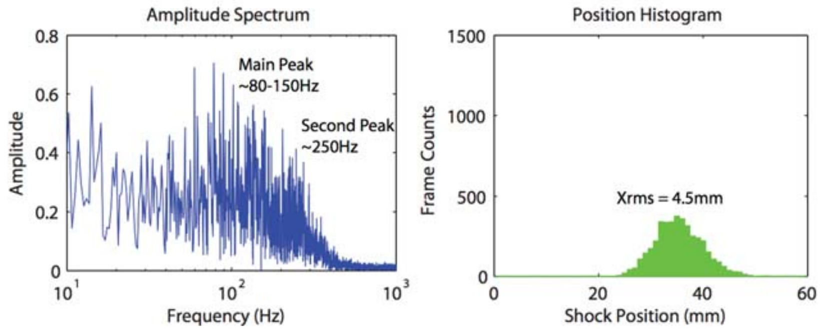
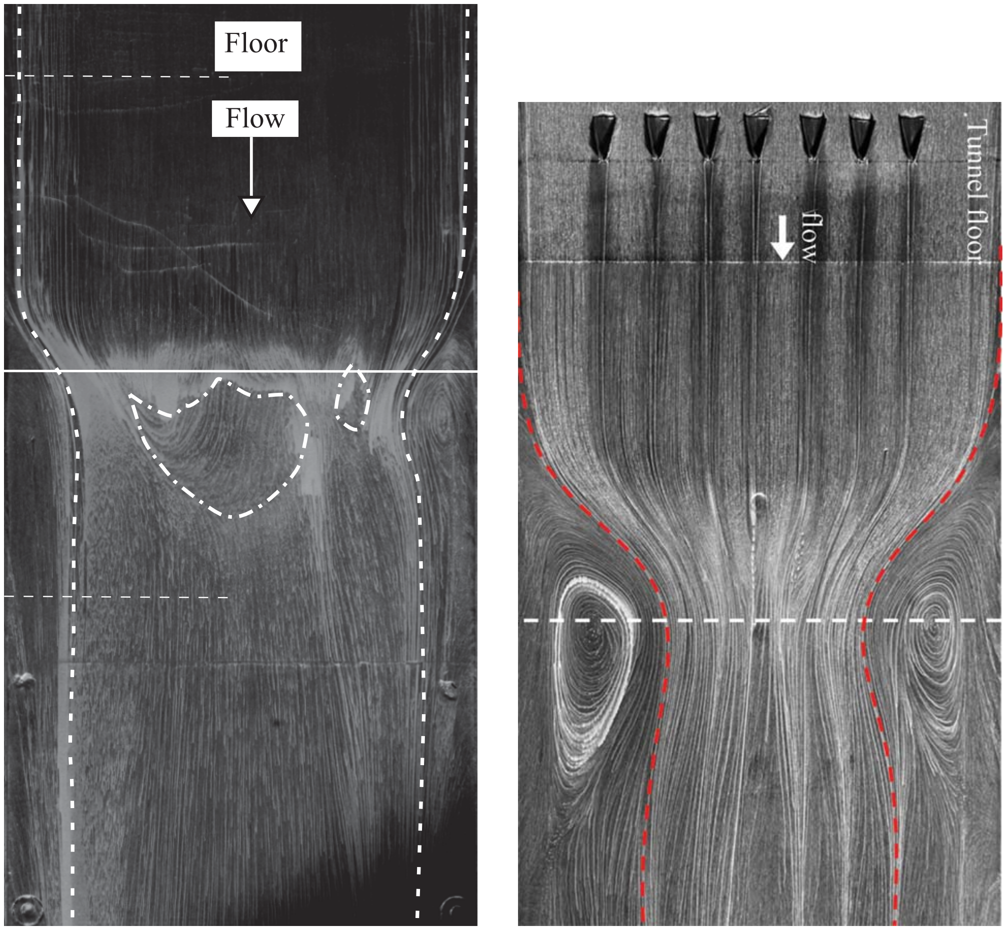


Figure 10: Frequency spectrum and histogram of shock position for the flow seen in fig .9.

4. The effect of flow control

All recent investigations into the control of SBLIs have shown that micro-vortex generators have the potential to delay or eliminate shock-induced separation [2, 5, 7, 9, 11]. However, studies of micro-VG control applied to normal SBLIs in rectangular channels [8] and in the 'inlet-relevant' normal-shock/diffuser flowfield [4] have clearly demonstrated that the 'central' separation (e.g. around the centre of the floor) is strongly coupled with the corner separation and vice versa. For example, fig. 11 compares the flow along the floor of a normal SBLI in a channel with and without vortex generators.



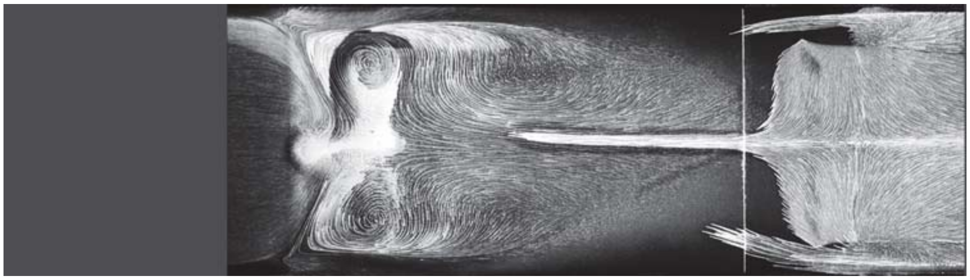
a) Baseline (no control) b) Micro-vanes ahead of the interaction

Figure 11: The effect of micro-VG separation control on the surface flowfield in a normal SBLI (flow top to bottom)

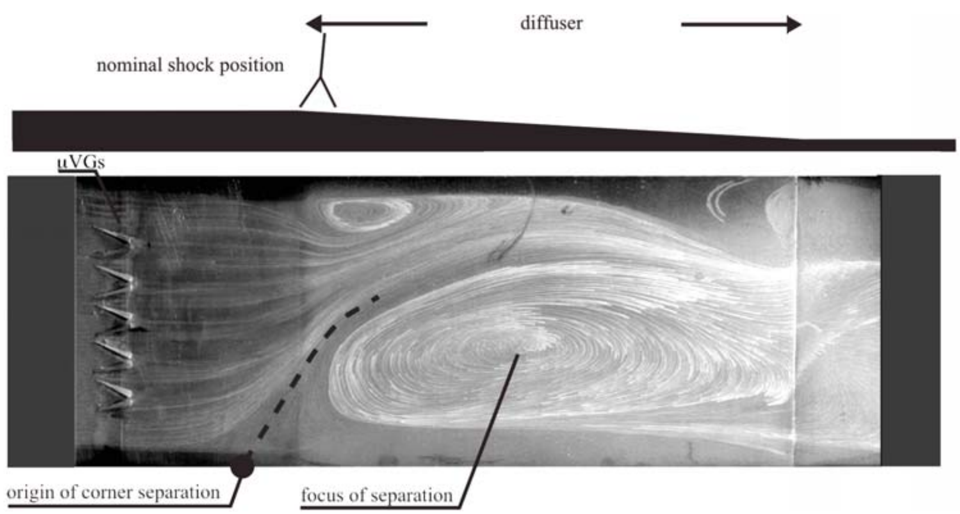
In the uncontrolled flow (fig. 11a) a typical separation pattern is seen, featuring a small region of recirculation around the centre of the tunnel floor and extensive corner separations on either side. When VG control is applied (fig. 11b) the central separation disappears but the size of the corner separation increases considerably. Thus the overall flow is not necessarily improved at all.

Similar observations have been made in the 'inlet-relevant' flowfield. Figure 12 compares the baseline with a micro-vane controlled flowfield. As discussed earlier, the uncontrolled baseline features considerable separation in the centre of the floor and the corners (note that both separations merge shortly after the diffuser entrance). When VGs are applied the central separation is eliminated and an attached flow channel forms. However, corner separations are greatly increased and the flow in the diffuser has become asymmetric.

This illustrates a further common finding: When corner separations become very large, they can interfere with each other to the point that symmetric flow becomes unstable and large asymmetries can be observed.



a) Baseline flowfield (no control)



b) With micro-vanes located upstream of the shock position

Figure 12: Surface flow visualisation in the 'inlet-relevant' flowfield with/without flow control

Such behaviour has also been reported in computations of normal SBLIs in straight channels [6]. It is currently thought that many turbulence models exaggerate the size of corner separations which is why this asymmetric behaviour is more common in computations than in experiments (see [6]).

While the above demonstrates that the size of any central flow separation in rectangular ducts has an effect on the separations seen in the corners, the opposite has also been found to be the case [8]. In extensive experiments where the size of corner separation has been modified by flow control it was found that central separations were noticeably affected. Similar, albeit somewhat more complex, behaviour appears to be present in supersonic shock reflections [11]. However, this remains a topic for current research.

This 'coupling' between corner separations and 'central' separations in trans/supersonic duct flows has a number of important consequences for flow control as applied to inlets:

- It is dangerous to draw conclusions based on the behaviour of one type of separation alone (corner or central). For example, flow control applied to the central region of one wall may not only have a direct effect on local separations but also an indirect effect elsewhere through modification of corner separations. Thus, by performing studies concentrating only along the centreline of a tunnel (or with inviscid sidewalls in CFD) it is possible/likely that erroneous conclusions about the efficacy of flow control are reached.
- A successful separation control in a normal SBLI or inlet-relevant flowfield must tackle all separation regions simultaneously. In particular, this requires that corner separations are controlled together with those occurring around the centres of channel walls.
- CFD can only be trusted if it is capable of predicting corner separations (and the effect of flow control on them). This remains a considerable challenge, particularly for RANS methods. The suitability of RANS turbulence models to predict corner separation remains unclear – not helped by a lack of validation quality corner flow data.

5. Combined micro-VG and corner bleed control of 'inlet-relevant' flow

Unfortunately, many years of research into vortex generator types of flow control has been unsuccessful at reducing or removing corner separations. To date, the only flow control method that has repeatedly demonstrated success at preventing (delaying) corner separation in SBLI flowfields has been localised suction[4] [9, 11]. Therefore, the most likely scenario for successful flow control in duct-like flowfields is a combined approach, utilising VG control away from corner flows and localised bleed to improve corner separations.

Thus, when small amounts of localised corner bleed[5] are used in combination with vortex generators, it is possible to significantly improve the flow in the 'inlet-relevant' flowfield as demonstrated by fig. 13.

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[4] Note that in the report 'bleed' and 'suction' are used interchangeably, in both cases referring to the active removal of air through a wall.

[5] In these experiments it has not been possible to exactly determine the bleed mass flux. However, typical values are well below 1% of the overall channel flow rate, of the order of 5-10% of the floor boundary layer mass flux.

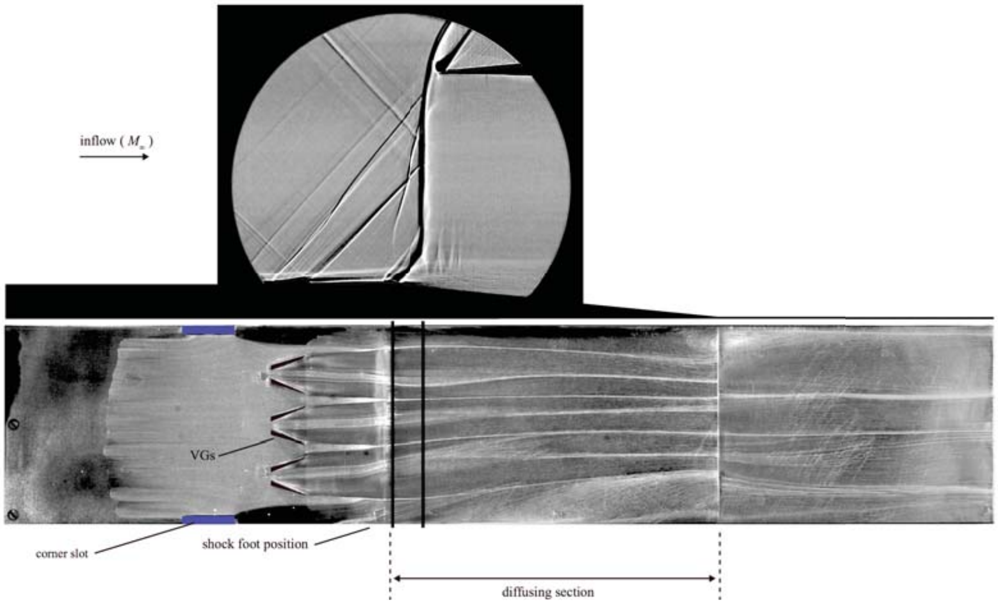

Figure 13: 'Inlet-relevant' flowfield with combined flow control (micro-vanes and corner suction). For baseline (uncontrolled) flow refer to fig. 8a.

The flowfield shown in fig. 13 is in the same geometry shown earlier in fig. 7 but with the application of corner suction and micro-vane flow control. This significantly improves the flow, achieving large amounts of attached flow throughout the diffuser. Detailed LDV velocity traverses in the central plane (seen in fig. 14) confirm that the flow remains attached for the controlled case (with a much smaller interaction region). The thickness of the low-momentum viscous region in the diffuser is consequently much greater in the baseline case compared to the flow with control.

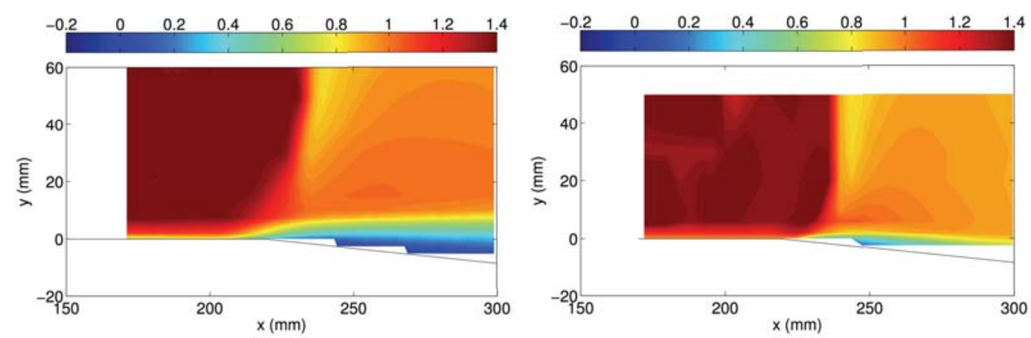

Figure 14: Mach number distribution along the mid-span plane for the baseline (left) and combined micro-VG and corner bleed controlled inlet relevant flowfield. Note the extensive separation observed in the baseline case combined with a large viscous region entering the diffuser.

Wall pressure measurements along the floor centre-line are presented in fig. 15 (along the x-axis x=0 is the location of the diffuser entrance). These show very clearly that the pressure recovery is greatly improved when flow control is applied. Further evidence of attached flow at the diffuser entrance is the existence of a distinct low-pressure spike at the corner. This is evidence of the expansion fan caused by supersonic flow turning into the diffuser. When the flow is separated at this location, this feature is absent because the separation bubble effectively reduces the core flow area, supressing the expansion.

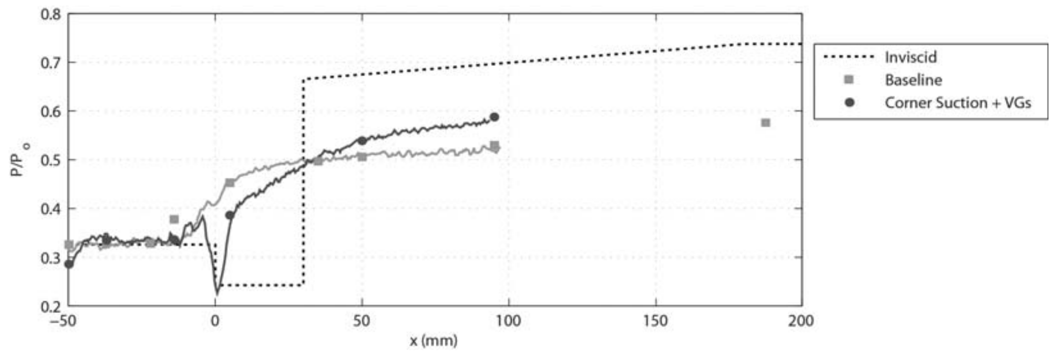

Figure 15: Centre-line wall pressure measurements for the baseline and combined control inlet relevant flowfield. Solid lines are pressure sensitive pain measurements while symbols indicate pressure tap data.

Downstream stagnation pressure surveys downstream confirm that this flow has been greatly improved through flow control [9]. This is seen by comparing the stagnation pressure map (measured downstream of the diffuser end[6]) for the baseline case (fig. 16) with that observed in the combined control case (fig.17). There are considerable improvements in the extent of the core flow as a result of the reduction on flow separation. Similarly, a reduction in flow separation as a result of flow control can be expected to yield benefits in flow distortion ahead of the engine face.

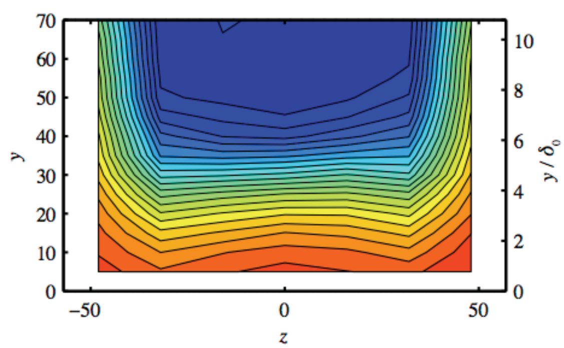

Figure 16: Stagnation pressure map downstream of diffuser end for 'inlet-relevant' flowfield (no control)

[6] Note: it was technically not possible to record stagnation pressure at the end of the diffuser, thus a degree of flow recovery has already taken place at the measurement location.

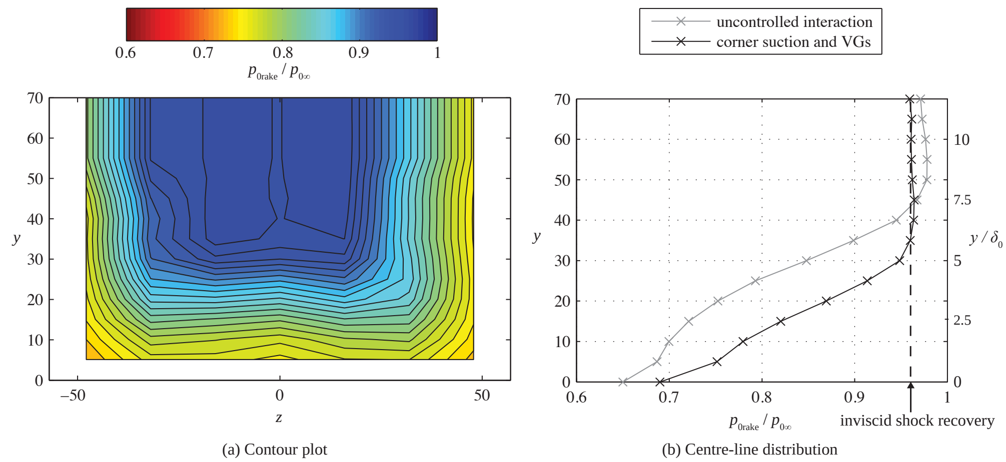

Figure 17: Stagnation pressure distribution for 'inlet-relevant' flowfield with combined control (micro-vanes and corner suction)

Similar experiments were performed on the un-stabilised shock-diffuser flowfield. Figure 18 shows flow visualisations for a flow controlled with corner bleed and micro-vortex generators (equivalent baseline image in fig. 9). Here, corner bleed mass flux was approximately 0.3% of the overall channel mass flux, which is approximately equivalent to 7% of the floor boundary layer mass flow rate. Compared to the improvements observed in the 'inlet-relevant' flowfield the current un-stabilised case shows slightly less reduction of separation due to combined VG/corner-bleed control (compare figs. 13 and 18). Nevertheless it can be seen that combined flow control has achieved considerably more attached flow inside the diffuser.

The surface pressure distributions of fig. 19 show that pressure recovery is greatly improved with the application of flow control and that the combined control outperforms the VG-only control. The relative improvements to the surface pressure recovery are very similar for the 'inlet-relevant' and the un-stabilised shock/diffuser flows (compare figs. 15 and 19). This is expected due to the close similarity in the overall pressure increase. Further details can be found in [13].

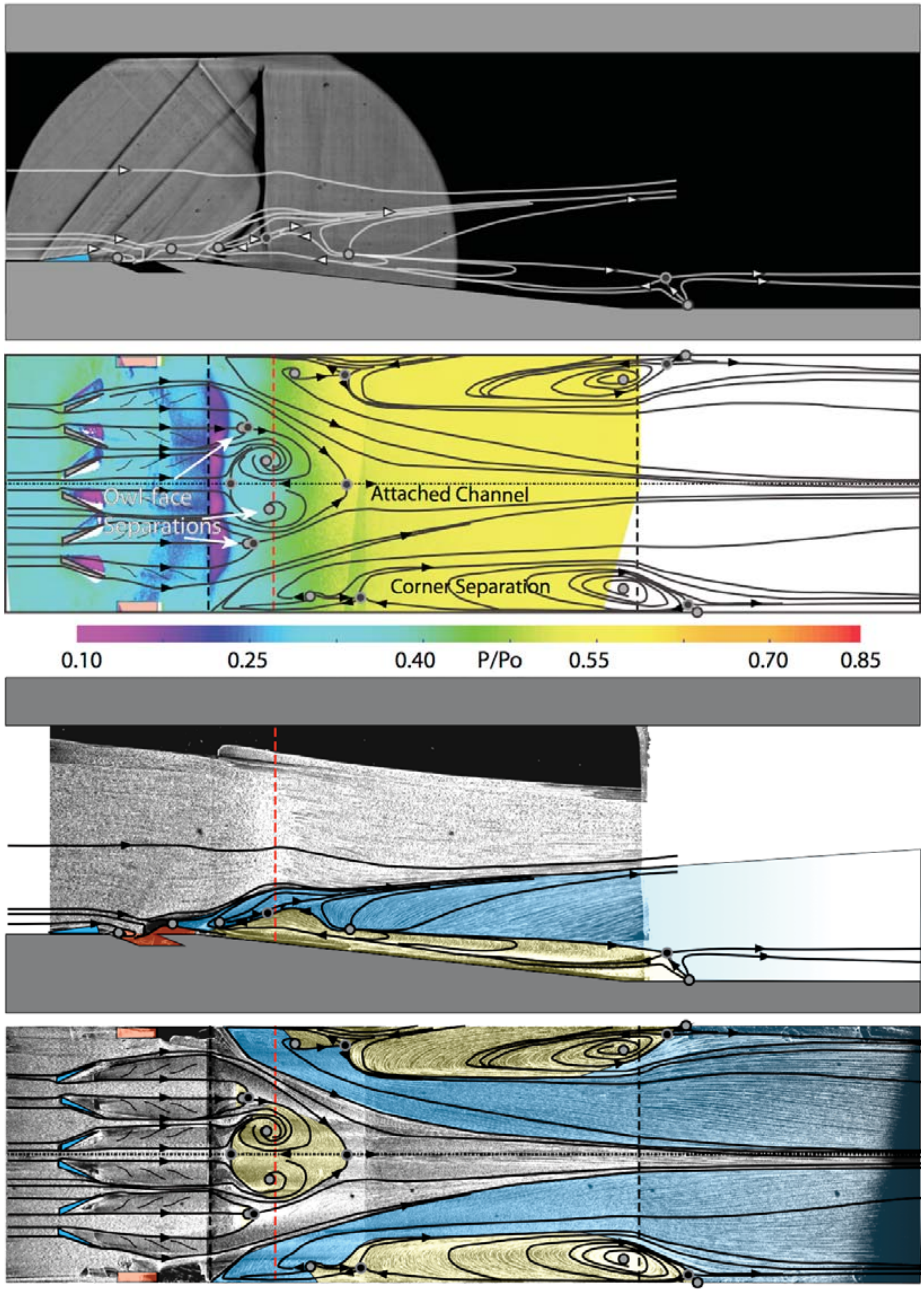

Figure 18: Compound image of schlieren (top), PSP (2nd from top), surface oil-flow (sidewall: 3rd from top, floor: bottom) and superimposed flow topology for the un-stabilised shock/diffuser flow-field controlled with corner bleed and micro-vortex generators. Equivalent baseline image in fig. 9.

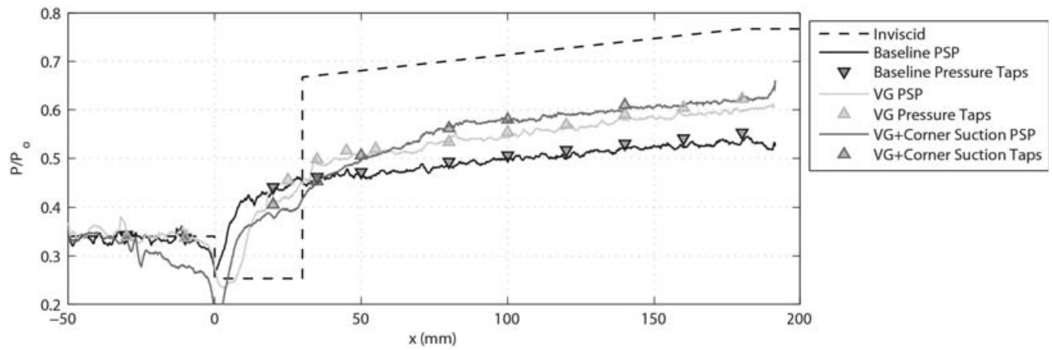

Figure 19: Centre-line wall pressures for the un-stabilised shock/diffuser flowfield controlled by micro-vortex generators with and without additional corner bleed.

Measurements of the unsteady shock behaviour seen in fig. 20 show that the shock oscillation has been reduced considerably through the application of flow control. This is apparent by the sharpening of the shock location histogram and the reduction in amplitudes in the FFT. Similar results were also reported in [7] for a different, but related, geometry.

while fig. 19 compares the wall pressure distributions for the baseline, VG controlled and combined VG/corner suction controlled flows. This shows that the combination of vortex generators for 'central' separation control and corner bleed to reduce corner separation gives the best results.

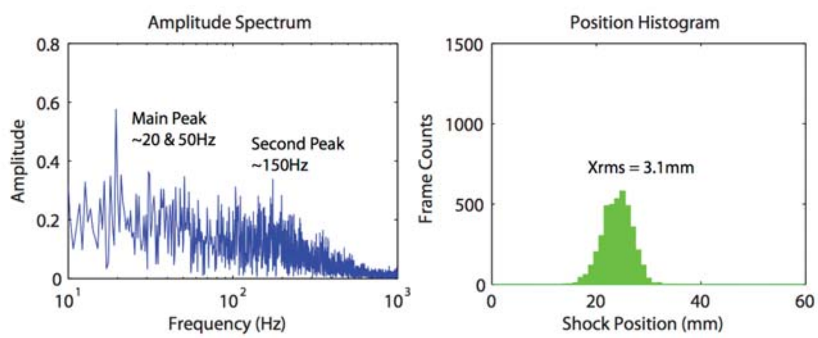

Figure 20: Frequency spectrum and histogram of shock position for the flow seen in fig. 18. Compare to the uncontrolled baseline case of fig. 10.

A further outcome of the various micro-VG studies is that it was found consistently that vane-type vortex generators perform better than ramp-type VGs [4, 5]. Typical sizes of effective micro-vanes are of the order of 50% of a boundary layer thickness and they generally need to be placed approximately 15-30 device heights ahead of the 'problem' region.

6. Comparison of micro-VG and bleed control

In order to evaluate the control potential of micro-VGs relative to the most widely used (and best-understood) control method of distributed bleed, experiments have been performed on the uncontrolled shock/diffuser rig with distributed suction. Here, bleed was applied in a region just after the entrance to the diffuser[7] (i.e. under the shock wave), spanning the width of the floor and extending approximately 3-4 incoming boundary-layer thicknesses in streamwise direction.

Figure 21 shows centre-line wall pressure distributions for a range of suction levels, expressed as percentage of floor boundary-layer mass flux.

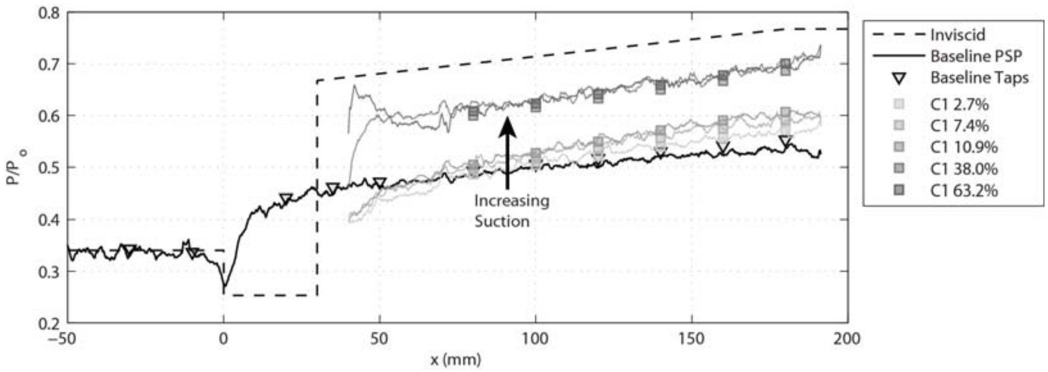

Figure 21: Centre-line wall pressures for the un-stabilised shock/diffuser flowfield controlled by various levels of distributed suction in the shock region.

This demonstrates that the 38% suction case achieves an optimum control effect – any further increases in suction level do not improve the diffuser performance. Comparison with fig. 19 suggests that the flow controlled through corner bleed and micro-VGs achieves a pressure recovery that lies in between distributed suction at 11% and 38%. As a first guess one might argue that this combined control is roughly equivalent to a mass removal of 20% of the incoming boundary layer. It is worth noting here that the mass flow removed through corner bleed is significantly smaller at about 7% of incoming boundary layer mass flux.

Figure 22 shows flow visualisation results for this configuration at the 'optimum' bleed rate of 38%. It can be seen that this configuration has a similar effect on the overall flow separation as the combined corner bleed/micro-VG control discussed earlier (fig. 18). The flow on the diffuser flow is now largely attached, however there remains a small patch of separated flow underneath the shock and significant separation in the corners (which appears to be increased relative to the baseline).

It can also be seen in the schlieren image (fig.22 top) that there is a fundamentally different shock structure in this flowfield compared to that seen with combined micro-VG/corner-bleed control. Because bleed removes significant mass flow the effective geometry of the channel/diffuser is changed. This particularly affects the local flow in the diffuser entrance region adding considerable flow re-acceleration. This in turn alters the shock structure as seen in the schlieren image.

[7] Bleed was also applied upstream of the diffuser but this was less effective at high suction rates. Full details are given in [13].

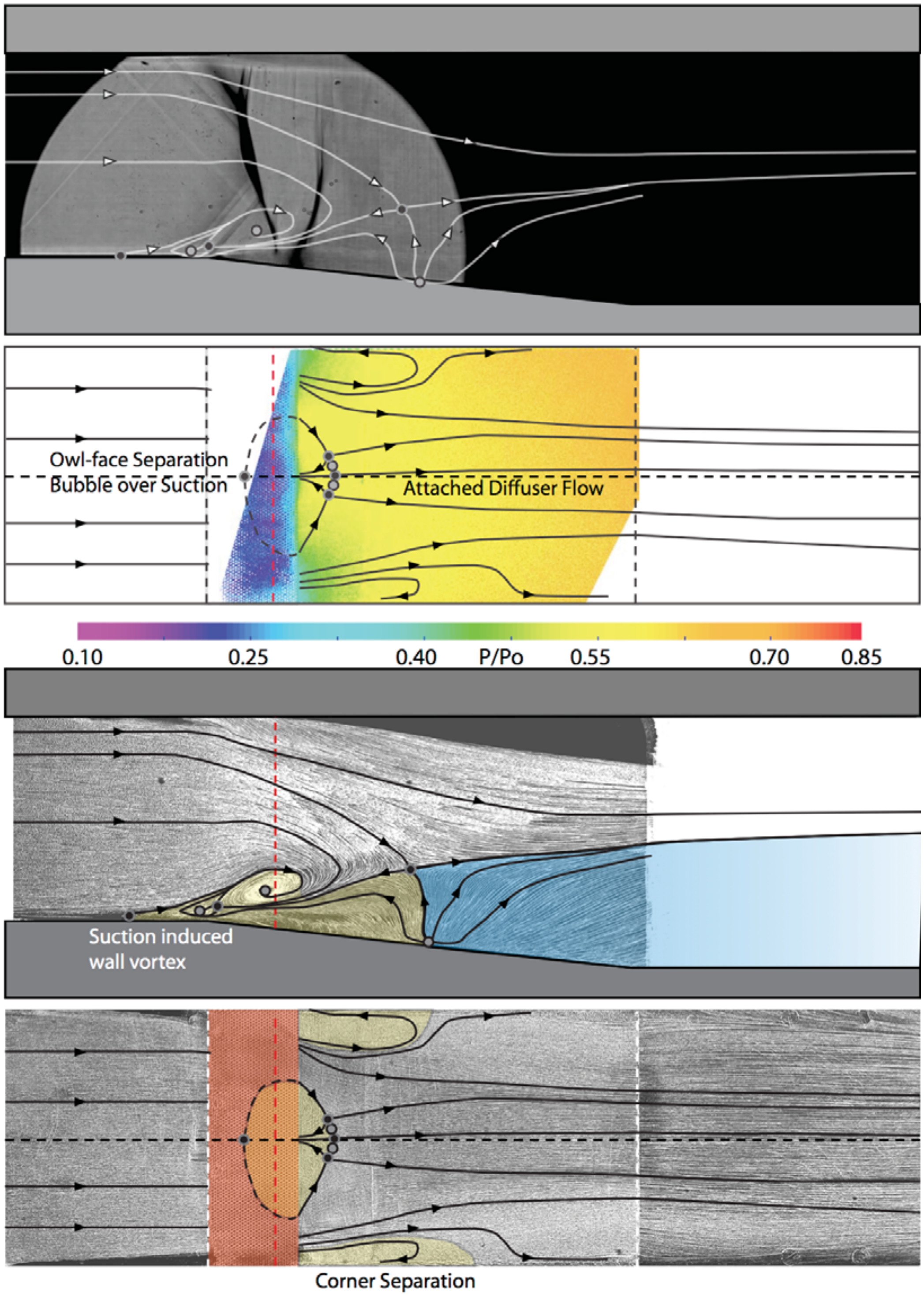

Figure 22: Compound image of schlieren (top), PSP (2nd from top), surface oil-flow (sidewall: 3rd from top, floor: bottom) and superimposed flow topology for the un-stabilised shock/diffuser flowfield controlled with distributed bleed just after the diffuser entrance (underneath the shock wave) – 38% of incoming floor boundary layer removed.

Distributed bleed has been found to be highly successful at reducing shock unsteadiness in the un-stabilised shock/diffuser flowfield. Figure 23 compares the spectra and histograms for shock motion for a range of suction levels between 4% and 63% of incoming boundary layer mass flux. It can be seen that even very small amounts of suction are very effective at stabilising the shock wave. This is explained by the fact that distributed bleed not only reduces (or eliminates) flow separation, but also acts as a 'shock trap' whereby the presence of a bleed patch directly underneath the shock wave offers significant passive control benefits (when the shock moves there is considerable change to the suction levels before and after to generate a strong restoring 'force' on the shock wave). Other types of flow control can not match this mechanism.

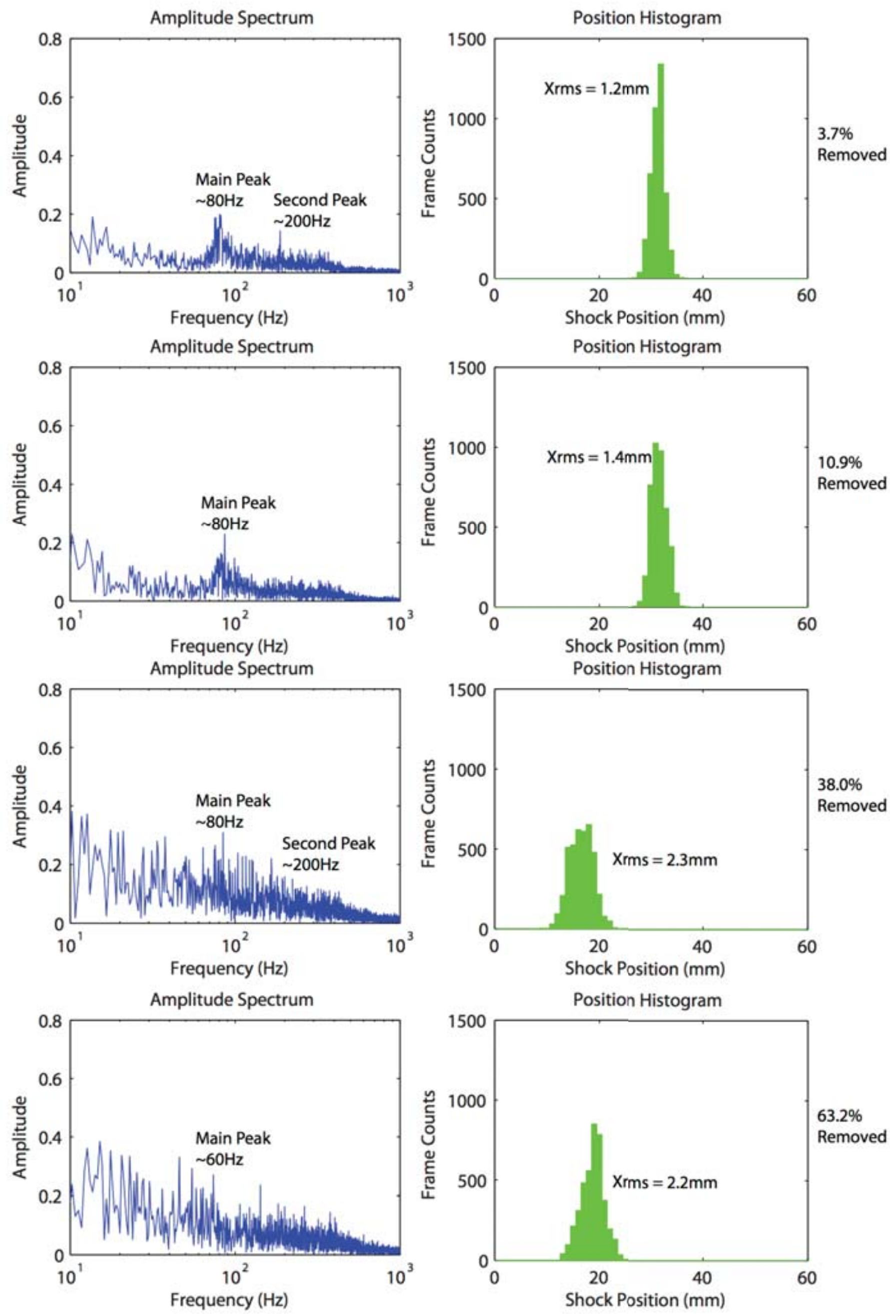

Figure 23: Frequency spectrum and histogram of shock position for the un-stabilised shock/diffuser flow controlled by distributed suction underneath the shock (see also figs. 21 & 22).

7. Conclusions

As a result of this research (and a few related studies supported previously or by Lockheed-Martin Inc.) the following 'lessons learned' appear to be relevant to future inlet design and development:

1. The flow in streamwise corners formed by the intersection of channel walls is more prone to separation than elsewhere. Therefore, in the presence of a shock-induced adverse pressure gradient the first onset of separation is generally seen in the corners.
2. The corner separation generates compression waves which alter the flow elsewhere. This can lead to a coupling between corner separations and other separations regions, e.g. in more central areas away from the corners.
3. In normal SBLIs this coupling often causes one type of separation to expand while the other shrinks and vice versa. Thus, flow control applied to one separation area can effect other problem regions as well – usually in the opposite sense.
4. In supersonic oblique shock reflection SBLIs a similar coupling exists. However, here the effects are more complex and they can lead to either an increase or a decrease of the central separation.
5. Computational predictions of shock-induced corner separations vary widely and there is insufficient validation quality experimental data.
6. The normal shock (or near-normal shock) /diffuser problem has been identified as a key element of inlet flow physics and a good test-bed for control strategies.
7. When the normal shock occurs some distance upstream of the diffuser the boundary layer can withstand both adverse pressure gradients reasonably well (there is no significant additive effect). However, when the shock-induced pressure rise merges with the diffuser adverse pressure gradient the flow becomes much more likely to separate. Thus, the typical mixed compression inlet scenario is considerably more aggressive than an external compression inlet flowfield.
8. Micro-vortex generators have considerable potential as separation control devices. They can delay or remove central separations very effectively. Vane types are more effective than wedge types.
9. Corner separation can be controlled through (very) small amounts of localised corner suction/bleed. To date, no vortex generator alternative for corner control has been found.
10. Distributed suction is very effective at improving inlet performance and reducing flow separation. Suction applied directly underneath the shock (at the diffuser entrance in the combined shock/diffuser problem) is more effective than suction applied upstream.
11. The normal shock/diffuser flowfield can be effectively controlled through a combination of corner bleed and vortex generators. This improves pressure recovery, distortion and unsteadiness. Compared to a suction-

only control system of similar effectiveness the additional use of vortex generators greatly reduces the bleed mass flow requirement.

12. Distributed suction still offers the most successful control strategy, if it is employed at high bleed rates (effectively removing almost half of the boundary-layer flow). However, in addition to the beneficial flow control effect, distributed suction also changes the effective duct/intake geometry and it is 'costly' in overall system performance terms.
13. Any control that reduces separation in the diffuser also has beneficial effects on the shock unsteadiness. However, depending on the type of flow control (e.g. VGs vs bleed) different physical mechanisms can be at work.
14. Vortex-generator flow control can only improve the flow's resistance to separation. By comparison, distributed suction also offer additional benefits, for example by acting as a 'shock trap' when it is applied directly underneath the shock.

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